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Aerosol Generation to Simulate Specific Industrial Fine Particle Effluents

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16. ABSTRACT: The article describes techniques that were developed to generate large quantities of fine particle metal oxide aerosols, by burning flammable solutions containing appropriate soluble compounds (nitrates) of the desired elements. In the flame these compounds generally decomposed to oxides. The generated aerosol flow rates were as ahigh as 42 cu m/min (1500 cfm); mass concentrations were as high as 16.8 g/cu m at STP. For most aerosols, particle concentrations were of the order of 10 to the 9th power part./cu m. Electron microscopic pictures (SEM and TEM) of precipitated particles show that many of the larger particles (20 micrometers) are hollow and that the smaller particles (0.01 micrometer) are aggregated. Specific aerosols were generated to simulate the fine particle effluents generated by combustion of pulverized coal (electricity generation), electric arc and basic oxygen furnaces (iron and steel production), and zinc smelters. Methods were developed to vary the SO2 concentration and the electrical resistivities of the simulants for coal combustion.

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Sulfur Dioxide	Stationary Sources	07B
Aerosols	Particulate	07D
Electrical Resistivity	Metal Oxides	20C
Aerosols Generators		13D
Dust		11G
Combustion		21B
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Techniques were developed for generating large quantities of fine particle metal oxide aerosols. The aerosols were generated by burning flammable solutions containing appropriate soluble compounds (nitrates, for example) of the desired elements. In the flame these compounds generally decomposed to oxides. The generated aerosol flow rates were as high as 42 m^3 per minute (1500 cfm); the mass concentrations were as high as 16.8 g per m^3 at STP. For most aerosols the particle concentrations were of the order of 10^9 particles per cm^3. Electron microscopic pictures (SEM and TEM) of precipitated particles show that many of the larger particles (20 μm) are hollow and that the smaller particles (0.01 μm) are aggregated. Specific aerosols were generated to simulate the fine particulate effluents generated by combustion of pulverized coal (electricity generation) electric arc and basic oxygen furnaces (iron and steel production) and zinc smelters. Methods were developed to vary the sulfur dioxide concentration and the electrical resistivities of the simulants for coal combustion.

Aerosol generation to simulate specific industrial fine particle effluents

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introduction

Fine particles (particles smaller than 5 μm), too small to rapidly settle to the ground, remain airborne for long periods. Because of their size, fine particles can penetrate deep within the human respiratory system and may have serious health effects depending on their compositions. Without improved control technologies, the impact of these air pollutants will increase with the worldwide expansion and growth of industrialization.

Laboratory pilot plant tests, used to improve control technologies for fine particle pollution-abatement, require stable sources of well-characterized fumes. To provide this, we have conducted research on the continuous generation of inorganic solid fine particulates. These aerosols are intended to simulate the fine particulate part of the effluents generated by combustion of pulverized coal for electricity generation, electric arc and basic oxygen furnaces, and zinc smelters.

The surfaces of many materials undergo subtle changes upon exposure to the atmosphere. Since the surfaces of particles can effect many of their physical properties, use of a flame method to produce fumes with freshly formed surfaces for many experimental applications should be superior to resuspension of collected materials. In most cases, burning flammable solutions more closely duplicates the actual effluent sources. It is also unlikely that submicron aggregates, shown to occur in the simulants in this paper, can be collected, then resuspended, so that they duplicate the aggregates contained in many industrial effluents. The simulation aerosols described in this paper are generated by burning flammable solutions.

The SO_2 content and particle resistivity of effluents generated by combustion of pulverized coal vary, depending on whether eastern or western coal is used. The fume SO_2 content and particle resistivity have a large effect on the collection efficiency of electrostatic precipitators which are installed in many coal burning plants. Since it is necessary to have coal fly ash simulation aerosols with various SO_2

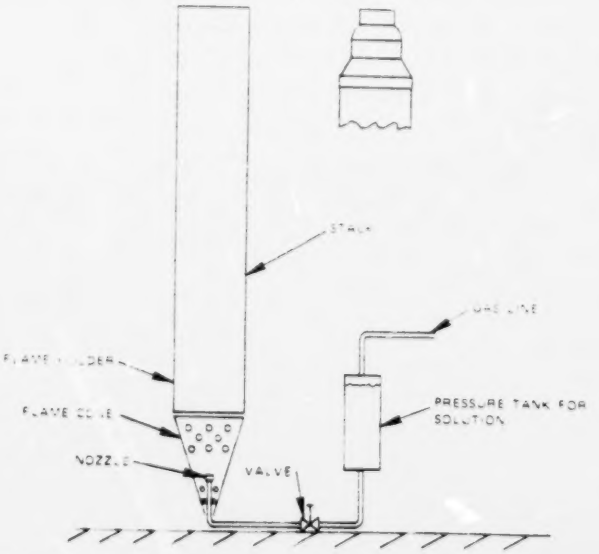

Figure 1 – Generator set-up for producing simulation aerosols. Reducer is sometimes used at top of stack to increase solids loading

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contents and particle resistivities in order to conduct all of the necessary precipitator tests; these simulants were successfully developed.

This paper describes the aerosol generation and sampling methods, gives chemical compositions, shapes, and concentrations of the generated aerosols and compares the simulation aerosols with the industrial effluents being simulated.

generation method

Solution-burning aerosol generators used for weather modification field experiments[1] were modified to dispense the required fumes. A flammable solution of appropriate chemicals was made and put into a heavy walled, stainless steel tank. The solution was pressurized with nitrogen gas, and, using a standard industrial nozzle, atomized into droplets. The droplets were burned to produce predominantly submicron particles of metal oxides by high temperature decomposition of the chemicals.

Figure 1 shows the aerosol generator and stack. The aerosol mass concentrations and exit temperatures were modified as necessary by using either a larger diameter stack or a reducer to increase or decrease the draft. Details of the hardware are given in reference 2.

solutions for simulation aerosols

Six basic solutions were used. The first, a basic solution for generating simulated fly ash, contained: hydrated aluminum nitrate ($Al(NO_3)_3 \cdot 9H_2O$), hydrated ferric nitrate ($Fe(NO_3)_3 \cdot 9H_2O$), dimethyl diethoxysilane ($(CH_3)_2Si(OC_2H_5)_2$), and ethanol (C_2H_6O). The second, a basic solution for generating simulated electric arc furnace effluent, contained: hydrated ferric nitrate ($Fe(NO_3)_3 \cdot 9H_2O$), hydrated chromic nitrate ($Cr(NO_3)_3 \cdot 9H_2O$), hydrated magnesium nitrate ($Mg(NO_3)_2 \cdot 4H_2O$), aqueous manganese nitrate solution (51% $Mn(NO_3)_2$), and ethanol. The third contained iron pentacarbonyl ($Fe(CO)_5$) and acetone (CH_3COCH_3). The fourth contained hydrated ferric nitrate ($Fe(NO_3)_3 \cdot 9H_2O$), hydrated calcium nitrate ($Ca(NO_3)_2 \cdot 4H_2O$), and ethanol. The third and fourth were for generating simulated basic oxygen furnace effluent. The fifth, a basic solution for generating simulated zinc smelter effluent, contained hydrated zinc nitrate ($Zn(NO_3)_2 \cdot 6H_2O$), hydrated cadmium nitrate ($Cd(NO_3)_2 \cdot 4H_2O$), vanadium oxide sulfate ($VOSO_4 \cdot xH_2O$), water, and methanol. Another solution for generating a less toxic simulated zinc smelter effluent, the sixth, contained only hydrated zinc nitrate and methanol. Ethanol could be used in place of methanol; with ethanol, the aerosol temperature was higher. The solution formula weights are given in reference 2.

To decrease particle resistivities, lithium salts ($LiNO_3$ and $LiClO_4 \cdot 3H_2O$) were added to the first basic solution for simulated fly ash; on decomposing in the flame they yielded Li_2CO_3 and LiCl, respectively. Carbon disulfide was also added to the first basic solution; on decomposing in the flame it yielded SO_2. Immediately after mixing CS_2 in the basic solution, there was a slight reaction with a few bubbles formed but this did not appear to be a problem. A solution with CS_2 was usable for a few hours after mixing.

Several other ethanol solutions, containing one or two of the compounds used in the six basic solutions, were also used to obtain aerosols with a simpler chemical composition for X-ray diffraction analysis.

safety

$Fe(CO)_5$ is considered very toxic. CdO, CS_2 and CH_3OH are also toxic; $(CH_3)_2Si(OC_2H_5)_2$ is probably toxic. Most heavy metals are classified as toxic when they exist as fine particle aerosols, so care must be exercised when using these materials.

aerosol sampling

When a solution of alcohol and metal nitrates is burned with excess air, the aerosol produced consists of solid metal oxide particles, carbon dioxide, oxygen and nitrogen gases and water vapor.

X-ray diffraction analysis was used to determine the chemical composition of the metal oxide particles. For these analyses, particles were collected by placing a rectangular water cooled nickel plated plate at a 45° angle at the top of the stack. The amount of collected material varied from a few milligrams to about a gram for a 6-minute burn time. A part of each sample was immediately sealed in a glass capillary tube for X-ray diffraction analysis.

Several of the generated aerosols were precipitated and photographed with a SEM and a TEM to determine the shapes of the particles being generated. The precipitated particles were also observed with optical microscopes. The larger particles ($D > 10\ \mu m$) were sampled by letting them impact a glass slide coated with adhesive; the smaller particles were thermally precipitated onto SEM and TEM grids.

For particle concentration and size distribution measurements, each generated aerosol was sampled and diluted continuously at the top of the stack shown in Figure 1, piped down to the laboratory (located just inside the building beside the generator) and simultaneously measured with three particle counters. A comprehensive description of the sampling and dilution system is given in reference 2. The three counters used were an Environment I, Rich 100, condensation nuclei counter (CNC)[A], a Model 3000 Whitby Aerosol Analyzer (WAA)[B], and a Model PC 200 ROYCO Optical Particle Counter (ROYCO)[C].

The CNC is designed to detect particles as small as 20 A in diameter over a wide concentration range (10^2 to 10^7 particles/cm^3). Reference 3, however, shows that this CNC is not as responsive to hydrophobic as to hydrophilic

[A]Environment/One Corp., 2773 Balltown Road, Schenectady, NY 12309

[B]TSI Inc., 500 Cardigan Road, St. Paul, MN 55164

[C]ROYCO Instruments Inc., 141 Jefferson Drive, Menlo Park, CA 94025

particles smaller than 0.07 μm. This difference in response becomes larger as particle sizes decrease. The CNC was calibrated at the factory a few months prior to its use. The WAA can measure particles in the size range 0.0075 to 0.6 μm. Its measurements give an equivalent sphere diameter based on the electrical charge and mobility of the particles. An Electrical Aerosol Analyzer (EAA)[B], which had been calibrated at the factory just prior to its use, was used to calibrate the WAA. The constants used to convert the WAA outputs to particle counts were derived from this EAA calibration and are given in reference 2, Appendix C. The ROYCO measures particles in the size range of 0.3 to 10 μm; it measures the particle size in terms of the equivalent light scattering diameters of latex spheres. When the model PC 200 ROYCO and a Model 225 ROYCO were placed side by side and used to measure ambient aerosols, their outputs were in close agreement. The Model 225 ROYCO had been calibrated at the factory just prior to its use.

The mass distribution of the coal fly ash fume simulation aerosol was measured with a ten stage Celesco C-1000 cascade impactor equipped with quartz crystal sensors[D] [4].

Particle resistivities were measured with samples taken from the flame holder above the flame cone (see Figure 1) and also with samples collected by placing an aluminum screen at the aerosol exit at the top of the stack. Only a small amount of aerosol particles collected on the screen (about 2 grams) during six minutes of aerosol generation.

results

general

In most cases, the X-ray diffraction patterns of particles collected from the simulation aerosols generated by burning the previously described basic solutions were too complex to be easily interpreted. Clearer results were obtained by analyzing particles generated from solutions comprised of only one or two compounds. Table I lists the chemical compositions of the crystalline aerosol particles generated by burning certain flammable solutions containing only one or two compounds dissolved in either methanol or ethanol. The analytical results in Table I show that ethanol solutions containing hydrated nitrates of Fe, Mn, Cr, Mg, and Zn decompose on burning to yield certain oxides of these metals. The analytical results in Table I also shows that the burning of solutions comprised of ethanol and either hydrated aluminum or calcium nitrate or dimethyl diethoxysilane produces amorphous particles. Since the composition of amorphous materials cannot be determined by X-ray diffraction analysis, the amorphous materials were heat treated in an effort to crystalize them. The efforts were unsuccessful with the silicon and calcium containing materials but the material formed by burning solutions of hydrated aluminum nitrate and ethanol gave an Al_2O_3 diffraction pattern after being fired in a crucible at a high temperature. This is in agreement with the work of reference 5 which shows that Al_2O_3 prepared in a hydrogen and oxygen flame at 1700° K is amorphous; but when prepared at 3000° K, is crystaline. Further efforts to determine the chemical composition of the silicon and calcium containing materials by using analytical techniques were not made.

The preceding X-ray diffraction analyses are not useful to determine the chemical compositions of the simulation aerosols directly, except for the ZnO simulation aerosol (generated from the sixth basic solution). The X-ray diffraction analyses accompanied with microscopic examinations and chemical equations can be used, however, to determine the probable chemical compositions of the simulation aerosols. Table II shows the probable particulate chemical composition of the simulation aerosols generated from each of the six basic solutions. The composition of the

TABLE I
Particle Composition

Compound (grams)	Solvent(s) (liters)	Particle Composition (X-ray diff.)
$Fe(NO_3)_3 \cdot 9H_2O$ $Ca(NO_3)_2 \cdot 4H_2O$	ethanol	Fe_3O_4 with some Fe_2O_3 (calcium not detected)
$Mn(NO_3)_2 \cdot 6H_2O$	ethanol	Mn_3O_4 (hausmannite)
$Cr(NO_3)_3 \cdot 9H_2O$	ethanol	Cr_2O_3
$Mg(NO_3)_2 \cdot 6H_2O$	ethanol	Face centered cubic MgO (periclase)
$Zn(NO_3)_2 \cdot 6H_2O$	ethanol	Hexagonal ZnO (zinkite)
$Zn(NO_3)_2 \cdot 6H_2O$	methanol	Hexagonal ZnO (zinkite)
$Cd(NO_3)_2 \cdot 4H_2O$	methanol	CdO plus a trace of $Cd(OH)NO_3H_2O$
$VOSO_4 \cdot xH_2O$	methanol & water	VO_2, V_2O_4, and V_2O_5
$Cd(NO_3)_2 \cdot 4H_2O$ $VOSO_4 \cdot xH_2O$ (excess)	methanol & water	Primarily $CdSO_4$, some CdO, $2CdO \cdot V_2O_5$, and VO_2, V_2O_4, and V_2O_5
$(CH_3)_2Si(OC_2H_5)_2$	ethanol	amorphous
$Al(NO_3)_3 \cdot 9H_2O$	ethanol	amorphous
$Ca(NO_3)_2 \cdot 4H_2O$	ethanol	amorphous

TABLE II
Probable Particle Composition of the Simulants

Simulation Aerosol for:	Generated from Basic Solution	Estimated Particle Composition
Coal fly ash	1	SiO_2, $Al_2O_3XH_2O$, Fe_3O_4, and Fe_2O_3
Electric arc furnace	2	Fe_2O_3, Fe_3O_4, Cr_2O_3, Mn_3O_4, and MgO
Basic oxygen furnace	3	Fe_2O_3
Basic oxygen furnace	4	Fe_3O_4 with some Fe_2O_3 and $Ca(OH)_2XH_2O$
Zinc smelter	5	ZnO, CdO, VO_2, V_2O_4, and V_2O_5 with some $CdSO_4$
Zinc smelter	6	ZnO

[D] California Measurements Inc., 150 E. Montecito Ave., Sierra Madre, CA 91024

coal fly ash simulation aerosol was estimated to be a mixture of particles consisting of SiO_2 and $Al_2O_3 \cdot XH_2O$ (possibly existing as a silicate) and particles of Fe_3O_4 and Fe_2O_3. This estimate is based on microscopic examinations, the X-ray diffraction analyses and chemical equations.

The estimated composition of the electric arc furnace simulation aerosol is based on the X-ray diffraction results shown in Table I and on the assumption that the reaction products from the combustion of four metal nitrates together in solution (the second basic solution) are not different from the reaction products from the combustion of the metal nitrates in separate solutions.

The particulates from the basic oxygen furnace simulation aerosol generated from the third basic solution ($Fe(CO)_5$ and CH_3COCH_3) were not analysed by X-ray diffraction. The particulate composition is estimated to be Fe_2O_3, based on the uniform red color of the particles when viewed in a microscope and the chemistry of burning $Fe(CO)_5$ with excess oxygen. The X-ray diffraction analysis of the basic oxygen furnace simulation aerosol generated from basic solution 4 shows that the iron nitrate decomposes to Fe_3O_4 with some Fe_2O_3. Since basic solution 4 contains a small amount of $Ca(NO_3)_2 \cdot 4H_2O$, the particulates must contain a small amount of some calcium compound. Based on chemical equations and X-ray diffraction analysis of particulates generated from pure $Ca(NO_3)_2 \cdot 4H_2O$ solutions, this compound is estimated to be amorphous $Ca(OH)_2 \cdot XH_2O$.

Based on the X-ray diffraction analyses shown in Table I and on the relative amounts of each material in basic solution 5, the zinc smelter simulation aerosol particles are estimated to be a mixture of ZnO, CdO, VO_2, V_2O_4, V_2O_5, with some $CdSO_4$.

The nominal chemical compositions appearing in Tables III, V, VI, and VII were calculated using balanced chemical equations and the solution formula weights given in reference 2.

Figure 2 shows a 20 μm diameter hollow iron oxide (probably Fe_3O_4) particle. Few of the submicron particles were seen as single spheres. Figure 3 shows a single 0.2 μm particle with several particles of about 0.01 μ in diameter coagulated with it. These particles were captured from the coal fly ash simulation aerosol. Figure 4 shows particles captured from the electric arc furnace simulation aerosol; they are primarily aggregates of 0.01 to 0.02 μm particles. For many of the aerosols generated, much of the aerosol mass appears to exist as aggregates.

Particle concentrations and size distributions were measured for each of the simulation aerosols and for other

TABLE III

Comparison of the Simulation Aerosol and Coal Fly Ash

	Aerosol	Fly Ash
Exit Temperature	450°K (177°C)	121-157°C
Flow Rate	42 m^3/min, 0.51 kg/s	
Mass Concentration (g/m^3)	0.66 at 450°K, 1.1 at STP	0.6-3.2 (D<5 μm)* at STP
Mass Median Diameter	1 μm (from Celesco Impactor)	~15 μm
Volume Median Diameter	0.2 μ (from WAA & ROYCO data)	
Nominal Chemical Composition (wt. %)	50% SiO_2, 30% Al_2O_3 and 20% Fe_2O_3	SiO_2, Fe_2O_3, Al_2O_3, CaO, MgO, Na_2O
Bulk Density (g/cm^3)	About 0.3, packed density 0.9	0.5 - 0.8
Electrical Resistivity (ohm cm)	2×10^{11} - 2×10^{12} at ambient temp **	10^9 - 10^{11}

*The mass concentration including those particles larger than 5 μm ranges from 2.3 to 12.8 g/m^3

**See also Table IV

TABLE IV

Particle Resistivity* of Coal Fly Ash Simulation Aerosol (T = 21°C, RH = 27%)

Aerosol	Collection Point	Measured Resistivity* (ohm cm)
Simulation aerosol without lithium	Bottom of stack	1×10^{13}
	Top of stack	2×10^{12}
With 0.43 g Li_2CO_3 added per g simulation aerosol	Bottom of stack	5×10^{8}
With 0.16 g LiCl added per g simulation aerosol	Bottom of stack	2×10^{8}
	Top of stack	2×10^{11}

*These resistivities were measured with small samples of material at room temperature and may not be comparable to standard resistivity measurements.

TABLE V

Comparison of Simulation Aerosol and Electric Arc Furnace Fumes

	Aerosol	Fumes
Exit Temperature	931°K (658°C)	100 - 1650°C
Flow Rate	13 m^3/min, 0.073 kg/s	
Mass Concentration (g/m^3)	1.2 (4.0 at STP)	0.2 - 5 at STP
Volume or Mass Median Diameter	0.2 μm* (volume)	0.3 - 5.4 μm (mass)
Nominal Chemical Composition (wt. %)	50% Fe_2O_3, 20% Cr_2O_3, 15% MgO, 15% MnO	Fe_2O_3, FeO, Cr_2O_3, SiO_2, Al_2O_3, CaO, MgO, MnO, ZnO, CuO, NiO, PbO, C, S, P, Alkalies

*Median of those particles sized and counted with the WAA and ROYCO.

TABLE VI

Comparison of Simulation Aerosols A and B and Basic Oxygen Furnace Fumes

	Aerosol A	Aerosol B	Fumes
Exit Temperature	764°K (491°C)	913°K (640°C)	290 - 1650°C
Flow Rate	10 m^3/min, 0.073 kg/s	13 m^3/min, 0.076 kg/s	
Mass Concentration (g/m^3)	6 (16.8 at STP)	1.8 (6.0 at STP)	4.6 - 23 at STP
Volume or Mass Median Diameter	1.05 μm (volume)	0.3 μm* (volume)	0.095 μm (mass)
Nominal Chemical Composition (wt. %)	100% Fe_2O_3	95% Fe_3O_4 & Fe_2O_3, 5% CaO	Fe_2O_3, FeO, MnO, SiO_2, Al_2O_3, CaO, MgO

*Median of only those particles sized and counted with the WAA and ROYCO.

TABLE VII

Comparison of ZnO Aerosol and Zinc Smelter Fumes

	Aerosol	Fumes
Exit Temperature	579°K (306°C)	160 - 482°C
Flow Rate	17 m^3/min, 0.16 kg/s	
Mass Concentration (g/m^3)	0.94 g/m^3 (2 g/m^3 at STP)	0.9 - 150 at STP
Volume or Mass Median Diameter	0.2 μm (volume)	0.4 - 15 μm (mass)
Particle Composition (wt. %)	ZnO	ZnO, PbO, CdO

aerosols generated from solutions containing only one or two compounds. A total of 26 aerosols were measured. Based on the WAA measurements and with one exception, the total particle concentrations of the aerosols at the stack exit are of the order of 10^9 particles per cm^3. The exception is the basic oxygen furnace simulation aerosol, generated from $Fe(CO)_5$ and acetone, which has 2×10^{10} particles per cm^3. The indicated particle concentrations with the CNC are about one-sixth of those with the WAA.

Based on WAA and ROYCO measurements, the calculated volume median diameters are less than 3 μ for 24 of the 26 aerosols which were measured. One aerosol whose particles are comprised of Cr_2O_3 and another aerosol estimated to be comprised of $Ca(OH)_2xH_2O$ particles have volume median diameters larger than 3 μm. Details of the particle concentrations and size distributions for the 26 aerosols which were measured are given in reference 2.

When solutions with the same formula were burned and the generated aerosols measured with the CNC, WAA, and ROYCO, the particle concentrations and size distributions were found to be stable and nearly identical. This is evidence that aerosols generated by the techniques described in this paper will be stable and reproducible, satisfying one of the requirements for laboratory pilot plant test aerosols.

All of the simulation aerosol flow rates should be satisfactory for laboratory pilot plant tests. The flow rates vary from 10 to 42 m^3/min (see Tables III, V, VI and VII). Aerosol flow rates depend primarily on the stack configuration (see Figure 1) and the stack configurations were chosen to adjust the draft of air into the burner so that each simulation aerosol would have the proper exit temperature and mass concentration to match those of the effluent being simulated. The solution formulae affect the

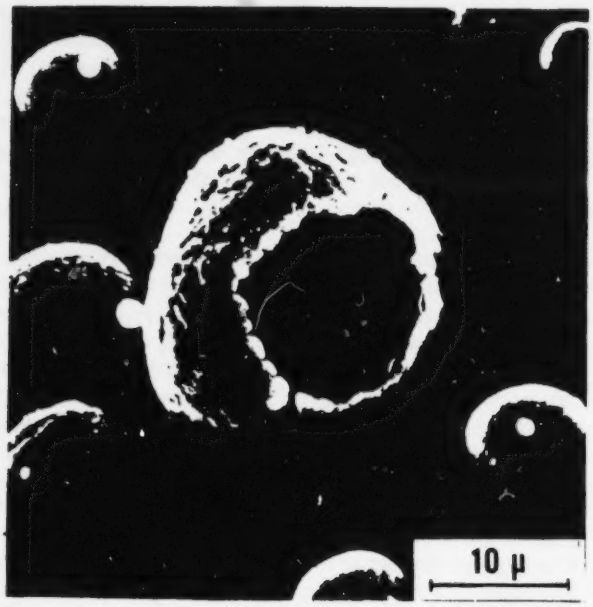

Figure 2 – Iron oxide particles from basic oxygen furnace simulation aerosol B.

aerosol flow rate to a lesser extent than the stack configurations.

coal fly ash fume simulation aerosol

When the solution for simulated fly ash is burned in excess air, the reactants and reaction products are estimated to be:

$$Al(NO_3)_3 \cdot 9H_2O + Fe(NO_3)_3 \cdot 9H_2O + (CH_3)_2Si(OC_2H_5)_2 + C_2H_5O + (\text{excess})O_2 \text{ \& } N_2 \triangleq Al_2O_3 \cdot xH_2O + Fe_2O_3 + Fe_3O_4 + SiO_2 + CO_2 + H_2O + O_2 + N_2 + \text{heat}$$

Table III shows several characteristics of the coal fly ash fume simulation aerosol and several characteristics of actual coal fly ash effluents. The fly ash characteristics shown in Table III are from reference 6, p. 53.

The characteristics of the simulation aerosol in Table III are similar to those of fly ash. The mass concentration of the simulation aerosol falls in the range of concentrations given for fine particle fly ash. The bulk density and electrical resistivity of the simulant also fall in the range of values given for fly ash. The simulation aerosol has an exit temperature slightly higher than that of fly ash (177° vs. 157° C). The simulant has a smaller mass median diameter than that given for fly ash (1 μm versus 15 μm) because only the fine particle portion of fly ash is simulated.

In Table III, there is a significant difference between the mass median diameter (1 μm) measured with the cascade impactor and the volume median diameter (0.2 μm) calculated from the WAA and ROYCO measurements. The cause of this was not determined. Most of the difference is probably due to the physical differences between particles (hollow spheres, aggregates, chemical composition, etc.) which have varying effects on the different measuring techniques of the three instruments.

The simulant contains oxides of silicon, aluminum and iron. In addition to these three oxides, "normal" fly ash contains, in smaller amounts, calcium compounds (lime, portlandite, anhydrite, calcite) and periclase. If it were desired to have a simulant with these additional compounds, then calcium and magnesium nitrates and carbon disulfide could be easily added to the basic fly ash simulation solution formula.

As mentioned in the *solution* section, lithium salts were added to basic solution 1 to show that the particle resistivity can be reduced. Lithium salts were tested and reduced the particle resistivity of the simulant particles as sodium salts do in fly ash. When $LiNO_3$ ethanol solutions burn, the major solid product is Li_2CO_3. Table IV shows the particle resistivity of the simulation aerosol with 0.43 grams of Li_2CO_3 per gram of SiO_2, Fe_2O_3, Fe_3O_4, and $Al_2O_3 \cdot 2H_2O$ and also another with 0.16 g of LiCl per gram of other solids. The resistivity of the simulant with Li_2CO_3 added was reduced more than six orders of magnitude. The resistivities shown in Table IV indicate that even at room temperature and low humidity there is a difference in the particle resistivities when lithium is present in the particles. A large amount of Li_2CO_3 (0.43 g Li_2CO_3 per g of total solid) was used in the simulation aerosol to measure an extreme resistivity case. Smaller amounts of either Li_2CO_3 or LiCl should be sufficient to adequately alter the particle conductivity.

electric arc furnace fume simulation aerosol

Table V shows several of the characteristics of the electric arc furnace fume simulation aerosol and of electric arc furnace fumes. The characteristics of the fumes shown in

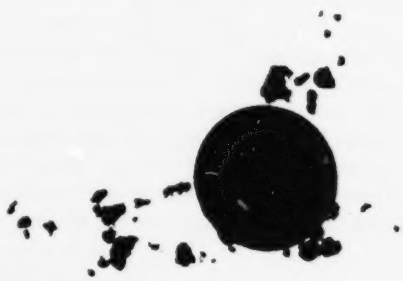

Figure 3 – Few of the submicron particles captured from the coal fly ash simulation aerosol were seen as single spheres.

Table V are from reference 6, pp. 123 and 126. The exit temperature, mass concentration and median diameter of the simulation aerosol all fall into the range of values given for electric arc furnace fumes. The nominal chemical composition of the simulant contains only four of the many metal oxides that electric arc furnace fumes contain. These four are, however, the major components of electric arc furnace fumes; the other metal oxides are present in smaller amounts.

basic oxygen furnace fume simulation aerosol

Table VI shows several of the characteristics of the basic oxygen furnace fume simulation aerosols and of basic oxygen furnace fumes. The characteristics of the fumes shown in Table VI are from reference 6, pp. 123 and 126. In Table VI, it is shown that there are two basic solutions for generating simulated basic oxygen furnace effluent. The first yields aerosol A which has a mass concentration of 6 g/m^3. The particles of aerosol A consist of hematite (Fe_2O_3). Aerosol A is generated from a solution of $Fe(CO)_5$ in acetone. The second solution yields aerosol B which has a mass concentration of 1.8 g/m^3. The particles of aerosol B consist primarily of magnetite particles (Fe_3O_4) with some hematite. Aerosol B is generated from a solution of $Fe(NO_3)_3 \cdot 9H_2O$ and $Ca(NO_3)_2 \cdot 4H_2O$ in ethanol. Based on a mass balance and on photographs of captured particles, aerosol B appears to have a large portion of its mass in particles with diameters greater than 10 μm. These particles are too large to measure with the instruments used to measure size distributions, thus the volume median diameter given in Table VI is likely to be too small.

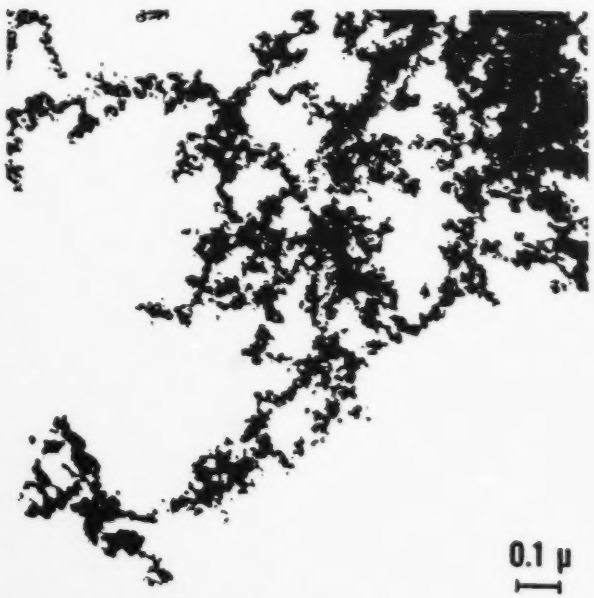

Figure 4 – The 0.01 to 0.02 μm particles captured from the electric arc furnace simulation aerosol were aggregated.

The exit temperatures and mass concentrations of both simulants fall into the range of values given for basic oxygen furnace fumes. The volume median diameters of both simulants are substantially larger than the mass median diameter given for basic oxygen furnace fumes. Since simulation aerosol A has a high mass concentration of highly aggregated particles, the volume median diameter could probably be reduced by burning a solution with the $Fe(CO)_5$ concentration lowered from that used to generate simulation aerosol A. It may be difficult, however, to generate a simulant with both a mass concentration as high and a mass median diameter as small as those of the basic oxygen furnace fumes; aerosols with median diameters as small as 0.1 μm and mass concentrations as large as 5 g/m^3 aggregate at a very rapid rate unless the particle sizes are nearly monodisperse.

The basic oxygen furnace simulation aerosols do not contain all of the metal oxides present in oxygen furnace fumes; however, magnetite and hematite typically comprise 90% of the mass of basic oxygen furnace fumes.[6]

zinc smelter fume simulation aerosol

Table VII shows several of the characteristics of a pure ZnO aerosol and of zinc smelter effluents. The characteristics of the effluents shown in Table VII are from reference 6, pp. 263-265. Pure ZnO aerosol generated from the sixth basic solution can be used to simulate zinc smelter effluents. Aerosol generated from the fifth basic solution can also be used. Because of a limited laboratory exhaust system and the toxicity of fine particle aerosols containing CdO, particle size measurements of this aerosol were not made.

The exit temperature and mass concentration of the ZnO aerosol fall into the range of values given for zinc smelter fumes. The volume median diameter of the ZnO aerosol is too small and is outside of the range of values given for zinc smelter fumes (0.2 vs. 0.4 to 15 μm). Based on visual observations of the burning of a solution containing $Cd(NO_3)_2 \cdot 4H_2O$ and $VOSO_4 \cdot xH_2O$, there is a strong possibility that the volume median diameter of a simulation aerosol generated from the fifth basic solution will be larger than the volume median diameter of the pure ZnO aerosol; the diameter may fall into the range of values given for zinc smelter fumes. As with the other simulation aerosols, the zinc smelter fume simulant does not contain all of the metal oxides present in small amounts in zinc smelter fumes.

conclusions

Solutions were formulated and upon combustion were shown to produce stable and reproducible fine particle aerosols to simulate each of four specific industrial effluents. The simulation aerosol particles vary in size from a few large (20 μm) hollow spheroids to aggregates of large numbers of 0.01 to 0.02 μm particles. Almost all of the aerosols have particle concentrations at the stack exit of the order of 10^9 particles per cm^3.

The simulation aerosol for coal fly ash fumes has a mass concentration, temperature, density, and resistivity similar to those given for coal fly ash fumes. The particle electrical resistivity and gas SO_3 content can be varied by adding certain chemicals to the solution used to generate the coal fly ash simulant. The electrical resistivity can be lowered over 6 orders of magnitude.

The simulation aerosol for electric arc furnace fumes has a mass concentration, median diameter, and exit temperature similar to those given for electric arc furnace fumes.

The simulation aerosols for basic oxygen furnace fumes have a mass concentration and exit temperature similar to those of basic oxygen furnace fumes. The median diameters of the simulant particles are substantially larger than those given for basic oxygen furnace fumes.

The simulation aerosol for zinc smelter fumes has a mass concentration and exit temperature similar to those of zinc smelter fumes. The median diameters of the simulant particles are smaller than those of zinc smelter fumes.

The chemical compositions of all the simulation aerosols have fewer ingredients than do the actual industrial effluents. The simulants contain only those materials which comprise the major portion of the effluents, but not those materials which the effluents contain in small amounts. All of the simulation aerosol flow rates should be satisfactory for laboratory pilot plant tests; flow rates vary from 10 to 42 m^3 per minute.

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